

# CORRELATION OF METALLIC FUSE/TAMPER CHEMICAL REACTION WITH ELECTRICAL RECOVERY

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## Abstract

Recent experiments have been conducted at NRL which were designed to evaluate the chemical reactivity of exploding conductor fuses and to relate the chemical process to fuse electrical performance. In these experiments, metallic fuses including aluminum wire and foils, lithium-aluminum alloy wire, and copper wire were vaporized in distilled water. Additionally, less precise tests were conducted where copper and aluminum conductors were vaporized in both  $\text{SF}_6$  and  $\text{CO}_2$  gases.

## Introduction

Aluminum and copper conductors, surrounded by an insulating tamper such as distilled water or pressurized gas, are used effectively as opening switches in pulsed inductive energy storage systems. Early experiments showed that water tamped aluminum fuses, when electrically vaporized, produced a proportionately large volume of hydrogen gas. Researchers speculated that appropriate selection of conductor cross-section to enhance chemical reactions could improve fuse electrical performance.<sup>1</sup> However, since there were few immediate applications for fuse opening switch technology, no additional work was completed for chemical reaction analysis.

Recent improvements in large-pulsed power energy storage systems such as high energy density capacitors or homopolar generators which utilize inductive intermediate storage components, and an interest by materials scientists in electrically initiated chemical reactions, has stimulated interest in continuing investigation of metallic conductor/insulating tamper chemical reactions. Aluminum and copper are the conductors of choice for such studies, since their electrical performance is well understood, and the materials are readily available in appropriate configurations,

## Electrical Operation

A metallic conductor may be heated to full vaporization by passing an electrical current pulse of appropriate intensity and duration through it. When the process is accomplished in 10s of microsecond times, thermal losses to the surrounding medium are negligible, and the amount of energy required to produce thermal transitions of the conductor through melting to full vaporization are well defined. For aluminum and copper, the energy required (starting at 20°C) is approximately 25 kJ/cm<sup>3</sup> and 40 kJ/cm<sup>3</sup> respectively. Typical electrical performance is represented in the voltage and current waveforms shown in Fig. 1. These waveforms have been segmented into a "conduction" phase, "opening" phase, "recovery" phase, and "dielectric hold-off" phase for purpose of definition.

In the "conduction" or low resistance phase, the metallic element exists as a solid conductor. Its properties, including dimensions, density, and resistivity are well known. In this phase the conductor remains at relatively low temperature and there are no significant chemical reactions involved.

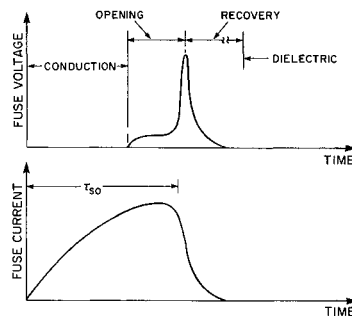


Fig. 1 Generic fuse electrical performance waveforms showing operating sequences of interest in fuse development studies

In the "opening" phase the metallic element initially becomes molten, and with additional joule heating, rapidly approaches full vaporization. During this process, its resistance increases rapidly, and thus performs as an electrical opening switch. Framing and streak camera photography show intense light output during this transition, and it is probable that significant chemical reaction processes are underway. Electrical performance for this phase is easily measurable, and accurate numerical models may be developed for predicting scaling of electrical performance.

The "recovery" phase refers to the short time duration between conductor vaporization and dielectric recovery, where the metallic element has been vaporized, but is in a conducting state, with electrical current decreasing rapidly as it is transferred from the fuse to some load. For example, Fig. 2 shows a typical experiment where load current is used to produce an intense electron beam. In these waveforms, the fuse completes its

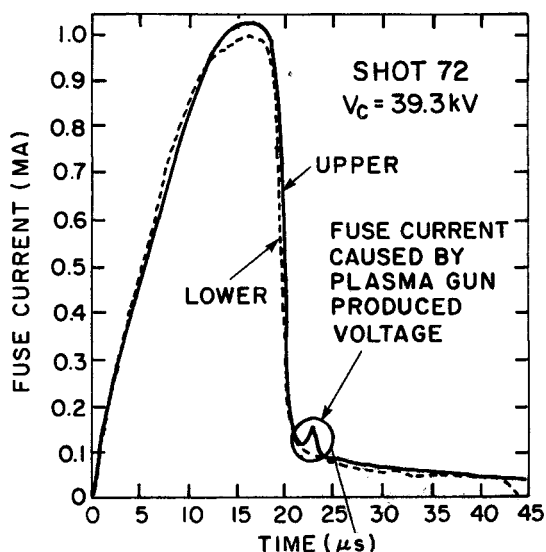


Fig. 2 Actual fuse waveforms showing parasitic losses resulting from load circuit impedance changes during fuse recovery phase

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"opening" phase at approximately 19.5 microseconds, coincident with the large (180 kV) voltage peak. At a time of 22 microseconds, the load circuit produces a high voltage pulse which, in turn, transfers a significant portion of load energy back into the fuse circuit. Thus the fuse, in its recovery phase, appears as a parasitic resistance in parallel with the load. Load circuit operation as well as the transitional nature of current and voltage in this phase make measurement and definition of electrical parameters difficult. As a result, the recovery phase is not well understood.

The "dielectric" phase occurs at some late time, after current has stopped flowing in the fuse. Performance may readily be measured for this phase and is usually defined in terms of kilo-volts per centimeter of electric field hold-off (dielectric strength) across the vaporized conductor. In this phase, the vaporized fuse has cooled and performs as an insulator (essentially no conduction) which, when over-stressed, forms a low resistance arc breakdown, usually termed "re-strike". Streak and framing camera show almost no light output in this phase, thus it is probable that chemical activity is low.

In attempting to relate the electrical performance to chemical performance, it is necessary to use two separate test circuits shown in Figs. 3 and 4. In the first circuit, a clamping (crowbar) switch is used to divert energy from the test sample at desired times. This circuit is used only for chemical reactivity measurements and may not be used for electrical hold-off and recovery measurements.

In the second circuit, the clamp switch is eliminated, energy conditions from the chemical tests are reproduced, and a second pulse circuit is used to provide recovery and voltage hold-off information.

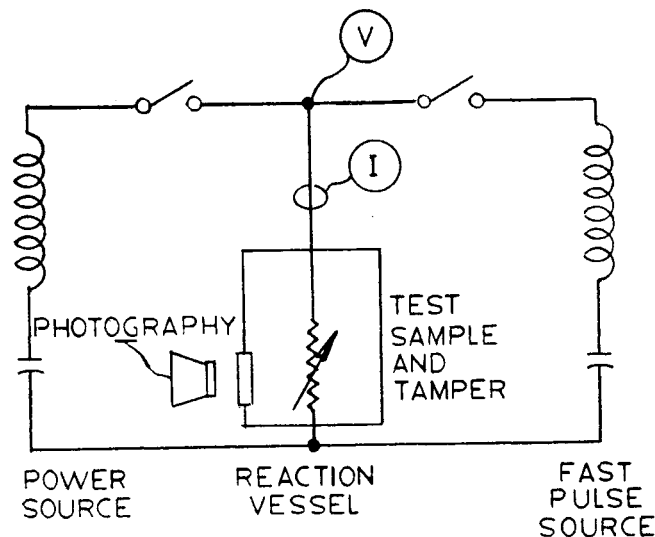
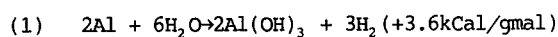


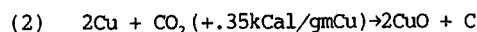
Fig. 4 Test setup used in measurement of fuse recovery performance.

#### Chemical Reactivity Measurements

Typical chemical reactions under study are as follows:



and



Two important considerations result from these equations. First, reaction (1) is strongly exothermic while reaction (2) is endo-thermic. It would therefore be expected that mechanical design for fuse holders may depend upon energy considerations related to type and strength of reaction. Second, the  $\text{Al-H}_2\text{O}$  reaction results in a clean and easy to measure reaction whose only gaseous by product is pure hydrogen. This reaction may be measured accurately using relatively straightforward techniques.

The circuit of Fig. 3 is used to measure chemical reactivity of aluminum, lithium aluminum alloy, and copper, each with a water tamper. The test sample is contained in an enclosed test chamber which contains a water tamper, an evacuated expansion volume, and a calibrated volume isolated by a valve. The storage capacitor, C, is charged to a selected voltage such that stored energy exceeds that required for full vaporization of the test conductor. Upon closure of switch S, the capacitor is discharged, via a pulse forming inductor L, and through the test sample.

As the test conductor is heated past melting, its resistance, and therefore its voltage drop, increases rapidly. With high voltage present, it is possible to close the clamping switch,  $S_2$ , and divert remaining stored energy away from the test conductor. During this process, a precise measurement of electrical energy input to the sample is obtained, and an accurate measurement of hydrogen gas may be calculated with an error of less than 5% based on pressure changes with and without the calibrated volume.<sup>2</sup> The amount of conductor material which was consumed chemically may readily be calculated using appropriate chemical formulas similar to equation 1.

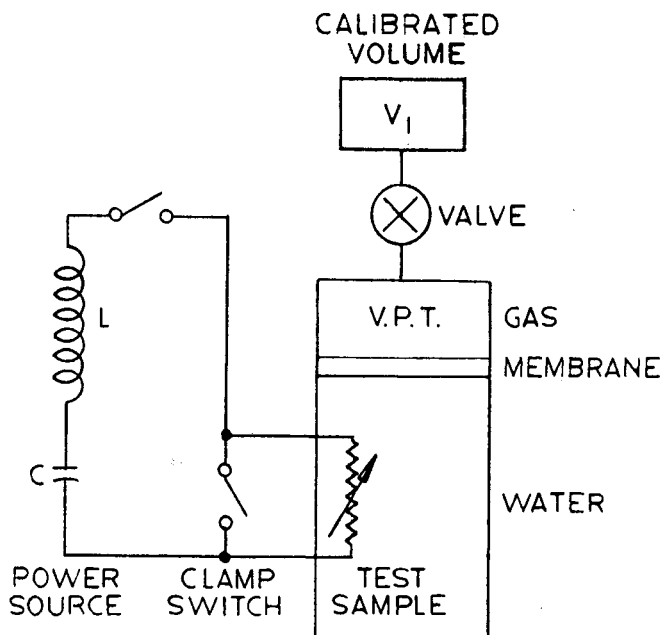


Fig. 3 Test setup used in measurement of fuse chemical reactivity vs. electrical energy input. Note that clamp switch prevents measurement of fuse electrical recovery.

The current and voltage curves of in Fig. 5 show electrical parameters for a series of typical tests. In the current and voltage traces the numbers 80 through 100 correspond to the timing pulse command for clamp switch closure. Actual closure typically occurs approximately 10 microseconds later, due to the switch operating characterisitc. The 80 microsecond command corresponds to the onset of the opening phase while the 100 microsecond point corresponds to completion of the opening phase for this example. Energy dissipated in the conductor is shown in the third family of curves for each set of conditions.

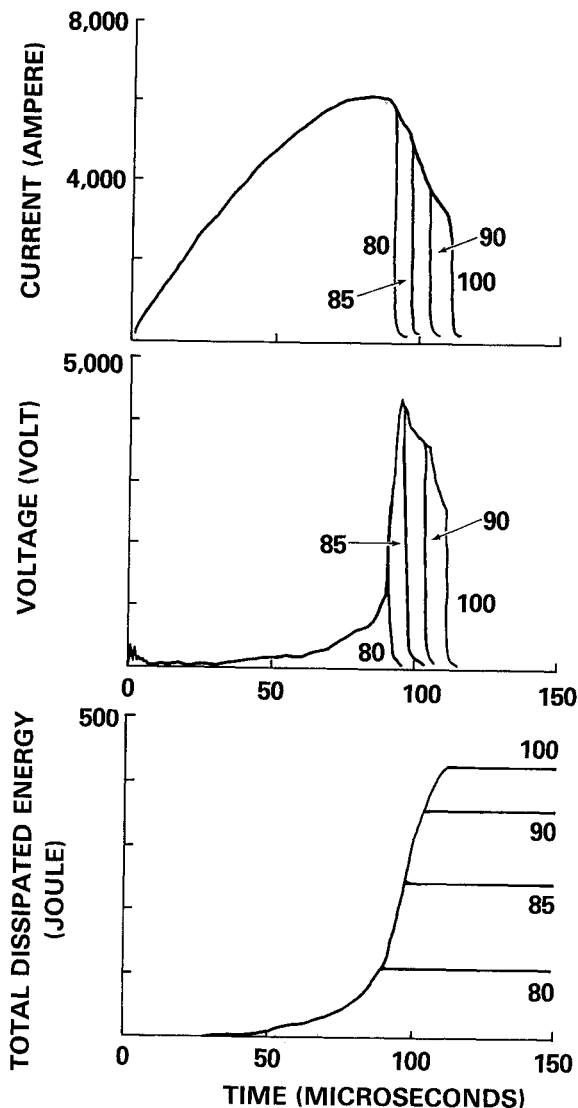


Fig. 5 Typical fuse electrical characteristics used in performing a series of chemical reaction measurements. Verticle lines labeled 80-100 depict times at which clamp switch triggering occurred.

The curves shown in Fig. 6 relate the electrical energy input to the level of chemical reactivity for two sets of conductors. For the pure aluminum sample, there is a direct relationship between electrical energy input and amount of conductor which is chemically reacted between onset of vaporization (2 kJ/gm) and full vaporization (10 kJ/gm). Note that these results do not identify the time of chemical activity, since measurements

were made much later, after the system has reached ambient temperature equilibrium.

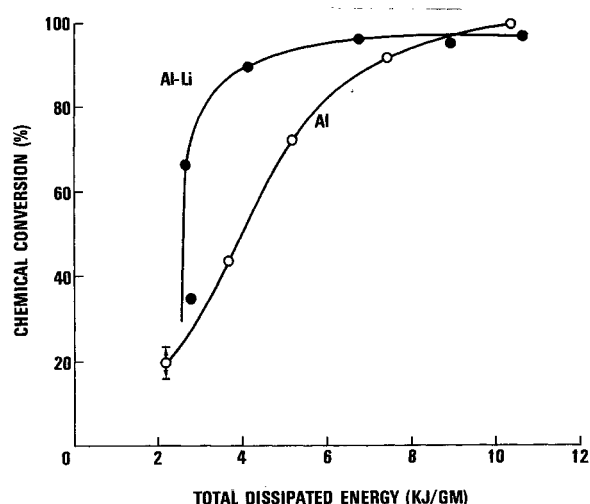


Fig. 6 Chemical reactivity for two conductor materials, resulting from electrical input parameters shown in Fig. 5.

When these tests are repeated using a physically similar (2% Li) aluminum alloy, it is observed that chemical activity is initiated at onset of vaporization. However, unlike pure aluminum, the alloy appears to undergo a self-sustaining chemical reaction until approximately 85% of its mass is consumed, without additional electrical input.

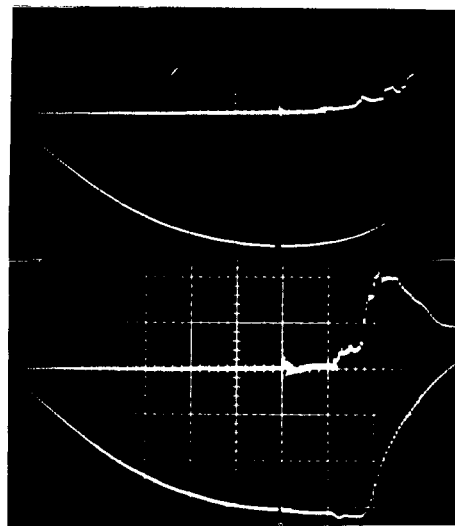


Fig. 7 Fuse electrical performance under identical electrical conditions, where a mechanical shockwave is used to disperse fuse material into tamper at the beginning of the opening phase. Upper traces show voltage, lower traces show negative going current. Timing is 10 microseconds per division.

One possible explanation for the above result is that the lithium contained in the alloy wire reduces surface strength of the oxide layer and assists rapid dispersion of the molten conductor into the water tamper. A simple additional test was conducted whereby an intense sock-wave was transmitted through the water in an attempt to rapidly disperse the pure aluminum conductor. It was observed that when the shock wave arrived simultaneous with onset of vaporization, there was a dramatic increase in the chemical reaction. The oscilloscope traces shown in Fig. 7 are

representative of the electrical performance with and without shock dispersion. System energy is identical for both traces, and the negative going current trace is identical for 60 microseconds. However, upon arrival of the shock wave (lower curves) there is a rapid increase in fuse resistance as shown by the rapid increase in voltage, and peak voltage occurs with only a 20% decrease in peak current for the shock-wave condition, as compared to a 70% decrease in current for the conventional vaporization process.

Similar tests were conducted where copper wire was used in place of aluminum. Chemical reactivity for copper with water tamper was low, with a maximum of only 30% of copper material reacted at full vaporization.

Additional tests were performed where either SF<sub>6</sub> gas or CO<sub>2</sub> gas was used in place of water. Only relative measurements were possible for these tests since recovery and measurement of the solid by-product materials was difficult. However, relative quantities of materials were collected after each test, and it was observed that only low levels of reactions occurred in gas at 1 atmosphere pressure. Significant by-products appear at pressure of 50 psi and continue to increase beyond 100 psi.

#### Electrical Performance Tests

Measurement of electrical recovery was conducted as shown in Fig. 4 using well known techniques<sup>3</sup> where a high voltage pulse is applied across the test electrodes at various times after fuse vaporization, and voltage and current are monitored to determine whether the fuse is conducting, withstands applied voltage, or re-strikes to form an arc. Note that in this circuit, it is necessary to remove the clamp switch, and to vary energy input by varying stored energy to obtain desired chemical reaction conditions. Chemical reaction results under these conditions are shown in Fig. 8. The differences in performance between the two types of conductors is less pronounced, since there is no means to interrupt energy as conductor material reaches the desired state of vaporization.

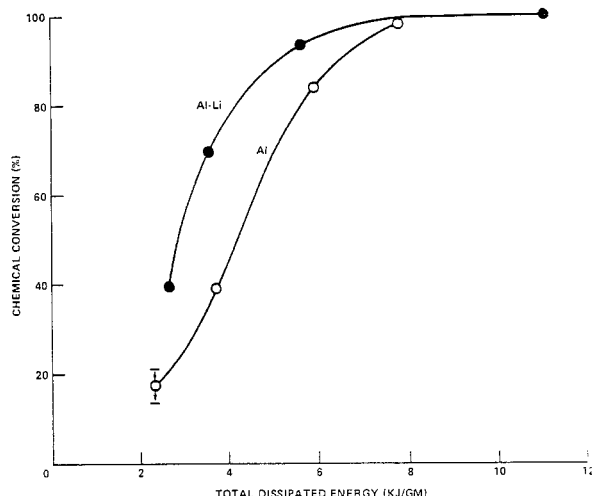


Fig. 8 Chemical reactivity measurements resulting when circuit of Fig. 4 is used and clamp switch is eliminated.

#### Test Results

Measurements were made of chemical reactions of various conductor materials with dielectric tamper materials of interest to the pulsed power and materials research communities. Precise measurements of chemical reactivity were obtained for all materials (al, li-al, and cu) when reacted with water using two different test circuits. By eliminating a clamping switch from the measurement system, it was possible to also obtain electrical performance for conductors in various chemically reacted states when vaporized in both water and gases. Results of these measurements are shown in Table 1.

#### SUMMARY OF CHEMICAL REACTION TESTS

Fuse Material	Material Reacted	Fuse Recovery	
Al. Wire	100%	Full (20 kV/cm)	} W T M
Li. Al Wire	100%	Full (20 kV/cm)	
Cu. Wire	30%	Partial (10 kV/cm)	
Al. Wire	Almost All	Full Dielectric Holdoff	} G T R M
Cu. Wire	Some (50 psi)	Partial (Resistive)	
	Almost All (100 psi)	Full (20 kV/cm)	
Cu. Wire	Some (50 psi)	Partial (Resistive)	
	Almost All (100 psi)	Full (20 kV/cm)	

\*WTPM = Water Tamper, Precise Measurement  
GTRM = Gas Tamper, Relative Measurement

Based on these preliminary results, it appears that high chemical reactivity which results in the formation of insulating by-products produces very good dielectric recovery. Similarly, when less complete reactions occur, as with copper conductor in water and copper in low-pressure CO<sub>2</sub>, the test sample remains in a high resistance, but conductive state, for the recovery times of interest.

#### Conclusions

It was demonstrated that intense chemical reactions occur when conductors are rapidly vaporized in conventional insulating tampers. It was found that the completeness of the reaction could be altered by varying parameters such as conductor chemical make up, tamper chemical make up, rate of dispersion of conductor, and energy input (temperature) of the vaporized conductor. These results demonstrate measurement techniques which may be useful to materials scientists in evaluating electro-chemical processes, and point out several techniques which should aid pulsed power engineers in simplifying fuse package designs and in developing more electrically efficient fuses.

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